A Portable Image Quality Analysis System: Design and Applications

Ming-Kai Tse, Quality Engineering Associates (QEA), Inc., Burlington, MA, USA

Abstract

Objective image quality analysis is critical to advancing the science, technology and business of imaging. In developing a line of portable image quality analysis tools, our goal has been to bridge a historic divide: sophisticated image analysis systems have been available to a relative handful of researchers in the laboratory; but practical, everyday tools for imaging professionals in other parts of the enterprise have been sorely lacking. In this paper, we summarize the functional requirements of a compact, low-cost tool and describe the hardware and software solutions incorporated in its design. We present application examples that highlight the capabilities, performance and potential of a system that makes on-the-spot image analysis a practical reality.

Introduction

Print quality is a key decision factor at many levels and in every facet of the imaging world. However, the subjective nature of print quality analysis and the complexity and high cost of the instruments required have hindered the adoption and growth of objective print quality analysis. To address these problems, QEA introduced a handheld image analysis instrument of novel design at NIP22. [1] In the short time since its introduction, it has proven its effectiveness thanks to its flexibility, functionality and ease of use. We believe it makes an important contribution to image quality evaluation technology. In this paper, we will describe user requirements and our hardware and software design solutions. System capabilities and performance will be discussed in light of important image analysis applications in digital printing.

User Requirements and Engineering Challenges

Users of image analysis systems rely on them for critical R&D information and for making important business decisions, among other reasons. To meet these needs, certain user requirements are essential in the design of an image quality analysis tool:

1. **Function and performance**: Dependability – reliability, accuracy, repeatability, and compliance with international or industry standards – is the most basic requirement.
2. **Ease of use**: To be truly effective, the tool must be easy to learn and easy to use; be simple to operate even for the most sophisticated analyses; deliver results quickly; and generate reports seamlessly.
3. **Flexibility**: To meet the diverse needs of the digital printing industry, it must be equipped with the latest analysis modules for analyzing the widest range of metrics.
4. **Upgradeable**: It must be upgradeable to the state of the art at all times.
5. **Portable and affordable**: For real impact on the industry, the tool must be widely available; compact, light-weight and portable; and low in cost.

This is not to suggest that large laboratory-based image analysis systems are obsolete. They certainly aren't. But given the dynamic growth of the digital printing industry, what is needed now is a tool that can be taken into the field to wherever the sample is, a tool that can quantify image quality anytime, anywhere.

Quantitative analysis is needed at every level of the imaging value chain, from researchers in the lab to users and decision makers throughout the industry. Everyone would benefit if analyses could be performed whenever and wherever they were needed, and a portable, low-cost image analysis system looks like the answer. The challenge, as illustrated in Figure 1, is making the transition from expensive, complex laboratory systems (say, ~100cm(H) x 100cm(W) x80cm(D) in size) to low-cost, compact systems and an order-of-magnitude reduction in size (to about 10cm in height) without sacrificing core functionality and performance.

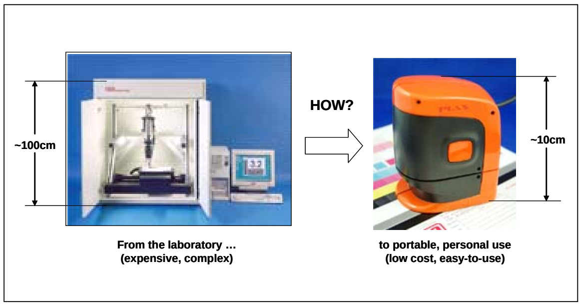


Figure 1. *The challenge of engineering a low-cost, portable image analysis system.*

Hardware Solutions

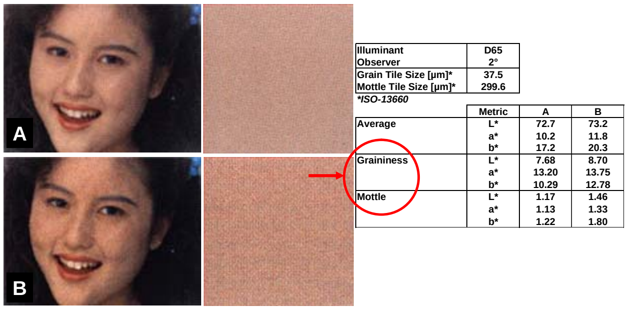
Several key innovations were required to respond to the engineering challenges. Figure 2 shows the current implementation. The main unit is on the right, with two of the available optics modules (left and foreground), and the control computer. Key elements of our hardware solution include:

1. **Camera**. A compact USB2.0 digital camera interfaces directly with the computer, which powers the unit; this eliminates the need for a battery inside the unit. A basic camera choice could be a single-chip color RGB camera, e.g. 1M or 640x480 pixels; or it could be a monochrome camera or a more advanced color camera with a higher pixel count or a 3-chip sensor for higher resolution, accuracy, and noise performance. The design has no fundamental limit (from either a hardware or a software

point of view) as to camera choice. We have implemented several versions incorporating standard pixel count or higher pixel count; color or monochrome; and visible or broadband spectral sensitivity. Thus, to meet different application and performance requirements, we have built into the design the flexibility to use different camera specifications. The user's ultimate choice depends on the product price point and the commercial availability of the camera.

Figure 2. *Portable image analysis system (right) shown with two optional optics modules (left and front) and an ultra-compact computer.*

2. **Optics**. We adopted the concept of interchangeable optics modules with fixed focus: each module can have a different resolution, aperture size (field of view) and illumination, and different spectral characteristics. This design approach is key to meeting requirements for flexibility and upgradeability. Our experience in image quality analysis has made it clear that different applications require different optical characteristics. For example:
    - Measuring dot, line and edge quality for modern digital printers requires high-resolution analysis down to the 3 to 5 μm range for dot size, line width, edge raggedness, and blurriness. Measuring mottle and coalescence in digital prints, on the other hand, does not need such high resolution, requiring instead relatively low magnification and a sufficiently large field of view to correspond to how we perceive these image artifacts. These points are illustrated in Figures 3 and 4. Here, the same images from two different electrophotographic printers were analyzed for benchmarking purposes. In Figure 3, the images were analyzed using a "low" resolution (~37μm/pixel), large field of view (32mm x 24mm) optics module. Measurements included graininess and mottle in L*a*b* as well as the noise power spectrum. Based on the images and the analysis results, it is clear that Printer B is inferior to Printer A in terms of image noise. The low resolution module is useful for measuring image noise affecting perceived image quality. In Figure 4, however, the analysis objective is different. Here the goal is to understand why there is a difference in image noise between the two printers. In this case, a high-resolution analysis may be preferable for quantifying halftone (dot) characteristics. As shown, the mean dot size (dot gain) is about the same for the two printers, but the variability reported as "stdev" (standard deviation) and the dot "roughness" in terms of perimeter and circularity are clearly different (B >A), affecting levels of perceived image noise. The noise power spectrum also reveals several noise peaks below 5 cycle/mm, which also surely contribute to the perceived image noise.

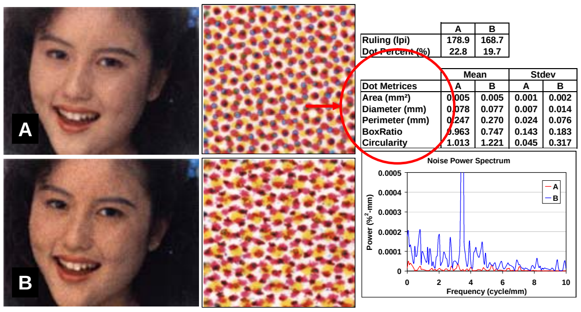


Illuminant Observer	D65 2°
Grain Tile Size [μm]* Mottle Tile Size [μm]*	37.5 299.6

**ISO-13660*

	Metric	A	B
Average	L*	72.7	73.2
	a*	10.2	11.8
	b*	17.2	20.3
Graininess	L*	7.68	8.70
	a*	13.20	13.75
	b*	10.29	12.78
Mottle	L*	1.17	1.46
	a*	1.13	1.33
	b*	1.22	1.80

Figure 3. *Graininess and mottle (image noise) analysis using a low resolution (~37μm/pixel), large field of view (24mmx18mm) optics module. (Images of the model is captured at low resolution for reference.)*



	A	B
Ruling (lpi)	178.9	168.7
Dot Percent (%)	22.8	19.7

	Mean		Stdev	
Dot Metrices	A	B	A	B
Area (mm²)	0.005	0.005	0.001	0.002
Diameter (mm)	0.078	0.077	0.007	0.014
Perimeter (mm)	0.247	0.270	0.024	0.076
BoxRatio	0.963	0.747	0.143	0.183
Circularity	1.013	1.221	0.045	0.317

Figure 4. *Halftone (dot) and noise power spectrum (NPS) analyses using a high resolution (~5.5μm/pixel, small field of view 3.5mmx 2.6mm) optics module. (Images of the model is captured at low resolution for reference.)*

- Different illumination geometries allow different image characteristics to be captured and analyzed. Some examples are the standard 45/0 configuration for diffuse, densitometric measurements; coaxial geometry for specialized applications (e.g. measuring halftone dots on flexographic printing plates), specular reflection for gloss measurements; and sharp-edge projection analysis for DOI (Distinctness of Image) measurements. [2] Figures

5 and 6 show images captured by two specialized optics modules: an infrared module in Figure 5 and a module with UV illumination to capture UV fluorescence in Figure 6, both of which have applications in security printing, forensic analysis and other specialized applications.

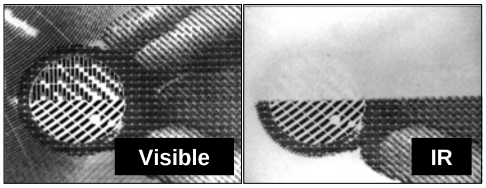


Figure 5. *Images captured in the visible range on the left and near IR on the right using a special IR optics module.*

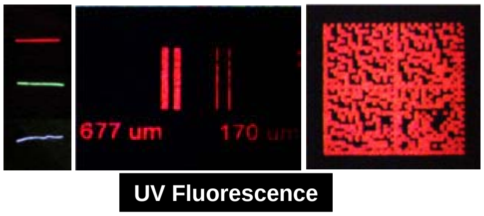


Figure 6. *Images captured in the visible range using a special optics module with UV illumination. The leftmost image contains UV fluorescent fibers embedded in a special paper.*

3. **Calibration.** One of the most important performance factors for any quantitative image analysis system is accurate calibration of spatial dimensions and reflectance. We put a great deal of attention and care in our design and the manufacturing process to address this. In general, since calibration is critical and requires specialized targets and specialized experience, we decided to perform calibrations in the factory and build the calibration information right into the optics modules. The information is stored in memory and every time an optics module is attached to the camera module, the control software in the computer reads the calibration information and applies it in all subsequent analyses and computations. Taking the burden of calibration off the user is important from the point of view of usability. However, the user may want the ability to verify that the system is performing optimally, so we offer an optional "Field Check Target" that has accurate lines, dots and reflectance reference patches for performance checking in the field. A properly calibrated system can achieve good performance, despite its compact design and conservative cost. For properly calibrated systems using the high-resolution module (~5μm per pixel), the standard error for line width measurements can achieve an intra-instrument agreement of better than 0.1% and an inter-instrument agreement on the order of 1%.

   Spatial dimensions are calibrated using a traceable, high-precision, chrome-on-glass Ronchi ruling to obtain x and y resolutions in μm/pixel. Reflectance and density are calibrated using a test chart with calibrated CMYK tone scales and correlating the measured camera RGB values and reflectance CMYK values obtained with a traceable spectrophotometer. Optical density is calibrated in different density standards including Status A, Status T, DIN and DIN-NB.

   Although accurate color measurement is not the purpose of our design, many users want the ability to estimate color values, for example in L*a*b*. To achieve this, we first convert measured RGB values into sRGB based on RGB-sRGB correlations empirically obtained during factory calibration in which a test target with known sRGB values is used. From the sRGB values, we then convert the measurements into L*a*b* values using known empirical sRGB-to-L*a*b* relationships. [3] Although the repeatability of this method of color estimation from camera measurements is good, the accuracy needs further improvement.

4. **Computer Requirements and Processing Capabilities**. Although the system design was intended for Microsoft Windows-based PCs, it can now be used on Apple MAC computers with Intel processors. This opens up even more applications for a broader range of users. Another area with good potentials for future expansions in our design is that additional electronics are built into the hardware to accommodate new developments in image processing and usability enhancements.

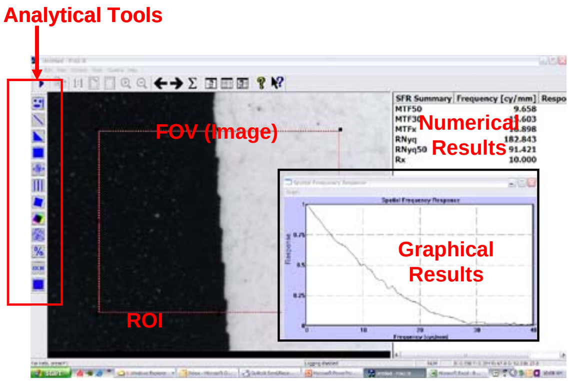
5. **Size, Appearance and Ergonomics**. Our design is compact – 5.5cm (W) x 8cm (D) x 10cm (H). It is light-weight (less than 350g) for portability and has an attractive industrial design that makes it look good and feel right in use. Controls (activation buttons) are also built-into the unit to improve productivity of the measurement process.

Software Solutions

For functionality and usability, the strength of a portable image analysis system lies in its software design. Some general software requirements include:

- An intuitive user interface
- Analyses in real time or using saved images
- Simple "one-click" operation
- Efficient interface with other applications (e.g., spreadsheet or database programs such as Microsoft Excel or Access) for reporting, further analysis, and data management
- Built-in expandability to accommodate new algorithms, software tools and future upgrades

A representative user interface is shown in Figure 7. A real-time display helps the user locate the unit in the area of interest within the field of view; define a region of interest for analysis; and launch the desired analysis (Analysis Tools at left). For most analyses, the results appear almost instantaneously in numerical and graphical form. For enhanced usability, results displays can be customized for individual applications. It should be noted that the analytical tools constitute an expandable set. This is a key design requirement in our software architecture for future expansion and enhancement.



SFR Summary	Frequency [cy/mm]
MTF50	9.658
MTF30	[illegible]
MTFx	[illegible]
RNyq	182.843
RNyq50	91.421
Rx	10.000

Figure 7. *A representative user interface of the control software.*

Analysis Toolbox and Applications

The power of an image quality analysis system lies in its software tools. An important design decision was the adoption, whenever available, of international and industry standards in the analysis algorithms. This is key. Individual companies may adopt proprietary methodologies or standards, but an industry-wide tool must be based on accepted standards. Further, the algorithms and parameters used in the analyses must be transparent to users to ensure clarity, understanding and acceptance.

The existing software toolkit contains an extensive set of tools for solving a broad range of common image quality analysis problems. These tools include many basic tools as well as some advanced, specialized tools. A list of tools (both general and application-specific) is shown in Table 1.

Table 1. Analytical tools and algorithms

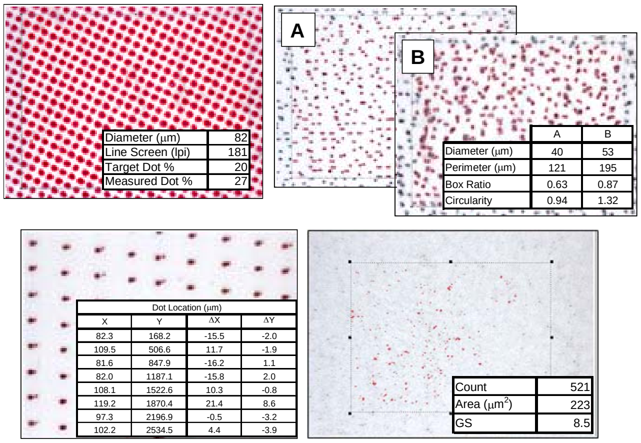
Software Tool	Typical Applications
Dot and Halftone Quality	Dot gain, dot shape, dot placement - xy locations Line screen, dot %, screen angle Inkjet satellites, toner background Voids
Line and Edge Quality	Width, blurriness, raggedness, contrast, fill, darkness (all based on ISO13660 [ref]) Text quality (stroke width, edge quality, darkness) Color adjacency and inter-color bleed Color registration error MTF (modulation transfer function)
Area Properties	Reflectance and density (in different density standards) Color (in L*a*b*) Graininess and mottle (image noise using the ISO13660 method, reporting in density, reflectance or L*a*b* units)
Noise Power Spectrum (NPS)	1D Fourier transform of a reflectance profile (in both horizontal or vertical directions)
Banding Analysis	Analysis of banding and streaking. Same algorithm as in NPS, but with the ability to convolve the spectrum with a VTF (Visual Transfer Function) to account for perceptual spatial sensitivity in interpreting the spectral results.
Spatial Frequency Response (SFR)	Compute the spatial frequency response (MTF or resolution) ased on the "Slant Edge" technique in ISO12233:2000. Same technique is also used to derive a new tool to compute color registration error (REG).
Other Useful Tools	Reflectance profile and histogram Color channel viewing Real-time display of the effect of thresholding

Dot Tool and Applications

Blob analysis is fundamental to all image analysis systems. The dot (blob) tool in our design is a general-purpose tool for a broad range of print quality analysis applications. Typical applications are:

- Halftone and dot gain analysis (for all printing technologies) (Figure 8a)
- Ink and media benchmarking (Figure 8b)
- Inkjet printhead quality control (Figure 8c)
- Toner background analysis (Figure 8d)
- Text quality analysis
- Forensic feature analysis and identification

In the dot analysis tool, software "intelligence" is needed to permit selection and identification based on color, polarity (dark or light), size, and shape (e.g., box ratio and circularity). The flexibility to use absolute or relative threshold and the ability to adjust edge-finding threshold levels serve to adapt the tool to different applications. Most dot analysis applications are performed at high resolution (e.g., halftone analysis, inkjet printhead quality or toner background measurement), but low resolution analyses may be more suitable for ink coalescence, feature identification, or text quality analysis applications.



Diameter (µm)	82
Line Screen (lpi)	181
Target Dot %	20
Measured Dot %	27

	A	B
Diameter (µm)	40	53
Perimeter (µm)	121	195
Box Ratio	0.63	0.87
Circularity	0.94	1.32

Dot Location (µm)			
X	Y	ΔX	ΔY
82.3	168.2	-15.5	-2.0
109.5	506.6	11.7	-1.9
81.6	847.9	-16.2	1.1
82.0	1187.1	-15.8	2.0
108.1	1522.6	10.3	-0.8
119.2	1870.4	21.4	8.6
97.3	2196.9	-0.5	-3.2
102.2	2534.5	4.4	-3.9

Count	521
Area (μm^2)	223
GS	8.5

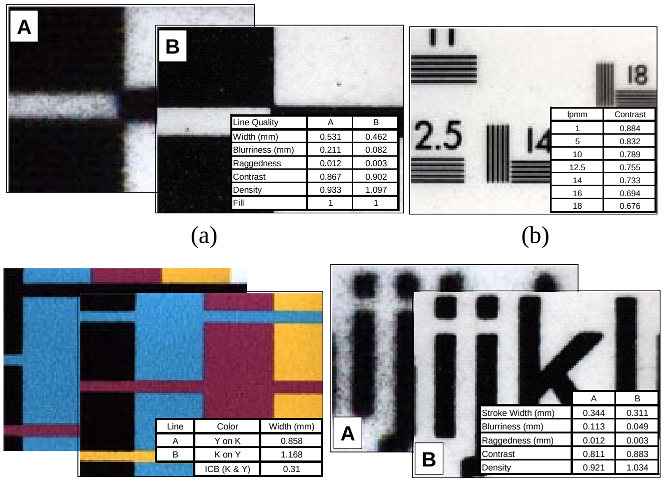
Figure 8. *Dot analysis examples: a) halftone and dot gain, b) ink and media benchmarking, c) inkjet printhead QC, and d) toner background.*

Line and Edge Tool and Applications

Quantitative line and edge quality analysis is central to all print quality evaluation. Line and edge quality attributes include line width, edge blurriness, edge raggedness, darkness (optical density), contrast and fill (voids). The high-resolution optics module is used for most of these measurements. Typical applications of the Line Tool are:

- Line bleed, blurriness, raggedness and darkness measurement (Figure 9a)
- Contrast and resolution estimation (Figure 9b)
- Inter-color bleed measurement (Figure 9c)
- Text quality analysis (Figure 9d)
- Color registration measurement

For line analysis, we adopted the methodologies specified in the ISO-13660:2001 international standard. [4] Our experience using this standard since its introduction has shown it to be a powerful tool that provides a common language and a consistent methodology for computing most of the defined attributes (with the possible exception of blurriness). The ISO-13660 methodology is generally straightforward to implement. For example, line width is obtained by the Relative 60% threshold in the reflectance profile (i.e., substrate reflectance=0% and colorant reflectance=100%). Blurriness, which is defined by the distance between the 10% and 90% reflectance thresholds, is more difficult to determine precisely because of the difficulty of consistently defining the R10 point on the reflectance curve. [5] Generally, though, ISO-13660 constitutes a significant contribution to quantitative print quality analysis.



Line Quality	A	B
Width (mm)	0.531	0.462
Blurriness (mm)	0.211	0.082
Raggedness	0.012	0.003
Contrast	0.867	0.902
Density	0.933	1.097
Fill	1	1

(a)

lpmm	Contrast
1	0.884
5	0.832
10	0.789
12.5	0.755
14	0.733
16	0.694
18	0.676

(b)

Line	Color	Width (mm)
A	Y on K	0.858
B	K on Y	1.168
	ICB (K & Y)	0.31

(c)

	A	B
Stroke Width (mm)	0.344	0.311
Blurriness (mm)	0.113	0.049
Raggedness (mm)	0.012	0.003
Contrast	0.811	0.883
Density	0.921	1.034

(d)

Figure 9. *Line tool examples: a) bleed, blurriness, raggedness & darkness, b) contrast & resolution, c) inter-color bleed, and d) text quality*

Area Properties Tool and Applications

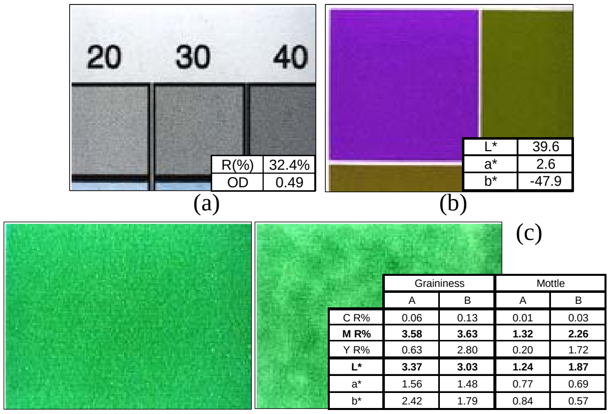
The most important function of the Area Properties tool is to quantify image noise such as graininess and mottle. In addition, it also measures attributes traditionally obtained with a densitometer or spectrophotometer. Typical applications are shown in Figure 10:

- Reflectance, density and toner reproduction (Figure 10a)
- Color in L*a*b* (Figure 10b)
- Graininess and mottle (Figure 10c)

It should be emphasized that for accurate density and color measurements an image analysis system is not a substitute for a well-designed densitometer or spectrophotometer. An image analysis system is typically a camera- or scanner-based measurement system not optimized to accurately reproduce the spectrum of the received signal from a reflective or transmissive measurement. In fact, it is typically a three channel (RGB) device that samples the measurement in selected frequencies (via color filters) and therefore only partially encodes the received signal. In our experience, if a careful calibration is performed, reasonably accurate density readings can be obtained, particularly if the calibration and measurements are made on the same combination of colorant and substrate. Similarly, if a color "profile" or a good look-up table (obtained using color management methodology) is available, one can expect fairly accurate and repeatable color measurement (e.g., L*a*b*) values. We recognize the limitations of a camera-based system for density and color measurements; but the benefits of being able to make density (and reflectance) readings and color estimations outweigh the limitations, in our view, provided that the user understands the limitations.

A very significant benefit of making color estimation such as L*a*b* values available is to make graininess and mottle measurements more "perceptually relevant". Let us elaborate:

1. Densitometers and spectrophotometers are designed to measure only the *average* value of density or reflectance in the field of sensor aperture, whereas an image analysis system can provide *non-uniformity* information such as graininess and mottle. This is the most significant advantage of an image analysis system over a densitometer or spectrophotometer.
2. In ISO-13660, graininess and mottle are computed and reported in the reflectance (density) space. Since the reflectance (density) space is not "perceptual," in principle, it is less relevant than, for example, L*a*b* in describing attributes such as graininess and mottle. For this reason, we take the step of converting reflectance (density) readings into L*a*b*, to provide more perceptually relevant image noise metrics.
3. While ISO-13660 specifies the scale (tile size) for computing graininess and mottle, we know from experience that tile size has to be adjusted to produce good correlation with subjective rankings of image noise. [6] Therefore, our Area Tool allows the user to specify graininess and mottle tile sizes.



R(%)	32.4%
OD	0.49

(a)

L*	39.6
a*	2.6
b*	-47.9

(b)

(c)

	Graininess		Mottle	
	A	B	A	B
C R%	0.06	0.13	0.01	0.03
M R%	**3.58**	**3.63**	**1.32**	**2.26**
Y R%	0.63	2.80	0.20	1.72
L*	**3.37**	**3.03**	**1.24**	**1.87**
a*	1.56	1.48	0.77	0.69
b*	2.42	1.79	0.84	0.57

Figure 10. *Area Tool examples: a) reflectance, density & tone reproduction, b) color L*a*b*, c) graininess & mottle.*

Noise Power Spectrum Tool and Applications

The Noise Power Spectrum (NPS) tool computes a one-dimensional Fourier transform of a reflectance profile. When applied to a spatial image, this is often called the "Wiener Spectrum." In practical terms, the Wiener Spectrum measures the noise variance at each spatial frequency, and the area under the NPS curve equals the total variance of the image. An artificial test image and its corresponding NPS are shown in Figure 11 to illustrate the physical meaning of the tool. A real-life application was shown in Figure 4 in the printer benchmarking application.

Banding Analysis and Applications

The algorithm behind the Banding Analysis Tool is identical to that of the NPS Tool. Essentially, it computes the one-dimensional Fourier transform of a reflectance profile, with the additional ability to convolve the resulting spectrum with a Visual Transfer Function (VTF) and highlight response in the spatial frequency range of greatest sensitivity to an observer. A Banding Tool application example is shown also in Figure 11, together with the NPS results to illustrate the effect of the VTF.

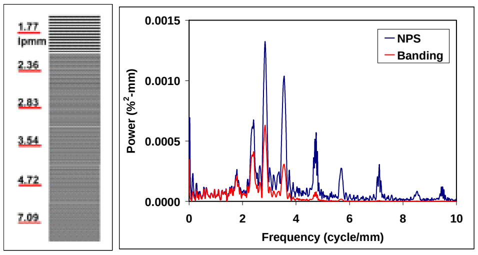


Figure 11. *Noise Power Spectrum (NPS) and Banding Tools.*

Spatial Frequency Response (SFR)

This is a unique tool based on an ISO standard originally designed for characterizing the resolution of digital cameras (ISO-12233:2000). [7] We found the tool useful for characterizing resolution on prints, and we have adopted it in one of the software tools in our design. In the SFR tool, Fourier analysis is used to compute an imaging system's spatial frequency response to a slanted edge. The slanted edge causes the edge gradient to be measured at many phases relative to the sensor, eliminating aliasing effects. The interpretation and analysis of an SRF curve is the same as an MTF (Modulation Transfer Function). An application example for the printer benchmarking case study discussed previously is shown in Figure 12.

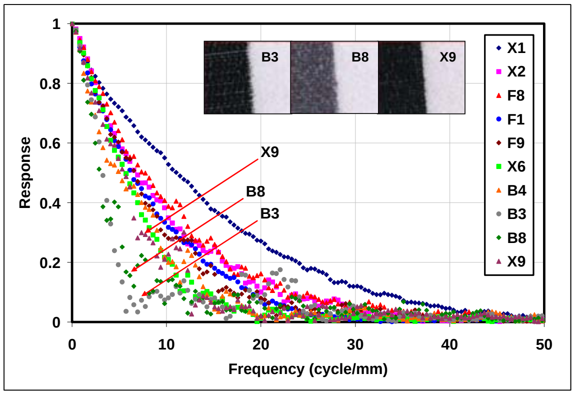


Figure 12. *SFR Tool for MTF (resolution) analysis.*

Summary

1. Objective image quality analysis is critical to the advancement of the science, technology and business of digital printing.
2. More and more imaging professionals are demanding reliable, easy-to-use tools to facilitate image quality evaluation and decision-making whenever and wherever needed.
3. To meet the needs and requirements of the imaging industry, we have introduced a second-generation portable image analysis system with many novel hardware and software design features.
4. We review user requirements including reliability, performance, ease of use, portability, flexibility, upgradeability and affordability.
5. We describe in detail the hardware design choices: camera, interchangeable optics, calibration methodology, computer options, system appearance and ergonomics.
6. The software tools are described in detail, with application examples demonstrating the capabilities of the design. The importance of incorporating a print quality standard such as ISO-13660 is discussed.
7. Our design offers the imaging industry a powerful and much-needed tool, one that promises to democratize the previously esoteric field of objective image quality analysis.

References

[1] PIAS™-II, A Second Generation Portable Image Analysis System. www.qea.com or info@qea.com
[2] M.K.Tse & J.C.Briggs, Distinctness of Image (DOI) of Inkjet Photo Papers, NIP21, p.492. (2005)
[3] www.brucelindbloom.com
[4] ISO/IEC13660:2001 Information Technology - Office equipment-Measurement of image quality attributes for hardcopy output-Binary monochrome text and graphic images
[5] J.C.Briggs, D.J.Forrest, A.H.Klein, M.K.Tse, Living with ISO13660: Pleasures and Perils, NIP15, p.421. (1999)
[6] J.C.Briggs, A.H.Klein, M.K.Tse, Applications of ISO-13660, A New International Standard for Objective Print Quality Evaluation, Japan Hardcopy '99, p.281. (1999)
[7] ISO 12233:2000 Photography-Electronic still-picture cameras-resolution requirements.

Author Biography

Dr. Ming-Kai Tse is the founder and president of Quality Engineering Associates (QEA), Inc. in Burlington, MA, USA. Prior to founding QEA, Dr. Tse was an Associate Professor of Mechanical Engineering at the Massachusetts Institute of Technology (MIT). His research interest is in measurement technology, with special application interest in digital printing and image quality analysis. He earned his BS at Cornell University and his SM and PhD at MIT. His is a Senior Member of IS&T. He can be reached at info@qea.com or +1-781-221-0080.